

# An Independent Assessment of a Subset of Hipparcos and Tycho-2 Proper Motions

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## Abstract:

The positions, proper motions, and parallaxes of  $10^5$  stars in the Hipparcos main catalog, derived from satellite data taken in the early 1990s, define the International Celestial Reference Frame at optical wavelengths. The Tycho-2 catalog is a  $25\times$  densification of the Hipparcos system, combining data from the Hipparcos satellite with those from a large number of ground-based astrometric catalogs produced over the last century. Tycho-2 proper motions have been previously shown to be comparable, in the aggregate, to those in Hipparcos (Urban et al. 2000) for stars in common.

In this pilot study, we assessed the external accuracy of the proper motions for a selected subset of stars in the Hipparcos and Tycho-2 catalogs, using an independent source of data, the observational measures recorded in the Washington Double Star Catalog (WDS). The selected

stars make up 162 wide visual double star systems for which nonlinear orbital motion should be negligible over the almost two centuries for which WDS measures are available. For each of these pairs, we computed relative proper motions (B component minus A) in RA and Dec from the WDS measures of separation and position angle. We then compared these relative proper motions to those derived from the Hipparcos and Tycho-2 catalog data for each component.

The pair-by-pair differences in relative proper motion among the three catalogs indicate that Tycho-2 is significantly better matched to the WDS data than Hipparcos. Furthermore, this kind of three-way catalog comparison can provide unique estimates of the external proper motion errors in each catalog separately. This analysis shows that the underlying mean errors in the proper motions of individual stars are about 2.5 mas/yr for Tycho-2 and 3.5 mas/yr for Hipparcos, which is not inconsistent with the tabulated errors for the sample of stars studied here. A broader survey is planned.

# Two Catalogs: Which Has the Better Proper Motions?

The two highest precision astrometric star catalogs yet produced are the Hipparcos main catalog (ESA 1997) and the Tycho-2 catalog (Høg, et al. 2000), containing  $1.2 \times 10^5$  and  $2.5 \times 10^6$  stars, respectively. The Hipparcos positions, proper motions, and parallaxes were derived from satellite data taken in the early 1990s and define the International Celestial Reference Frame (ICRS) at optical wavelengths. The Tycho-2 catalog combines data from the Hipparcos satellite with those from 144 ground-based astrometric catalogs produced over the last century.

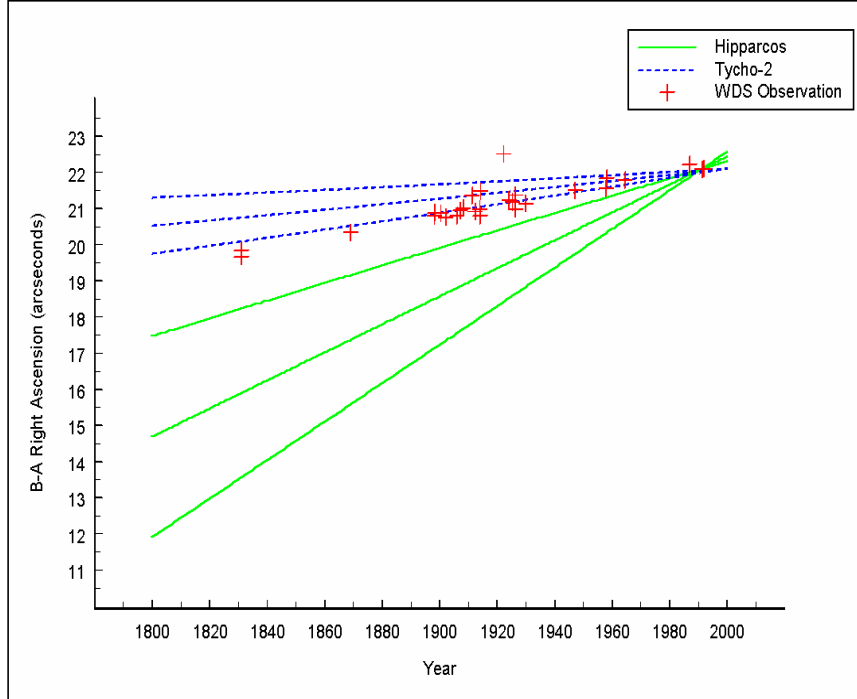
This paper investigates the proper motion data from these two catalogs. The Hipparcos proper motions represent a snapshot of stellar motions over about  $3\frac{1}{3}$  years centered at mid-1991, whereas the Tycho-2 proper motions represent the average stellar motion over most of the 20th century. Formal  $1\sigma$  uncertainties in proper motion are typically about 1 milliarcsecond per year (mas/yr) in Hipparcos and 1–3 mas/yr in Tycho-2. Urban, Wycoff, & Makarov (2000) showed that the distribution of the proper motion differences for *single* stars in common has a  $1\sigma$  width of 1.6 mas/yr. Nevertheless, for many individual stars, especially those in double systems, the differences in proper motion significantly exceed that expected from the formal errors. For these stars, is there a way that we can decide which proper motion — Hipparcos or Tycho-2 — is better? Can any generalizations be made regarding the relative quality of the proper motions in the two catalogs? To answer such questions, a third, independent source of high-precision proper motion data is needed.

# The Independent Data Set

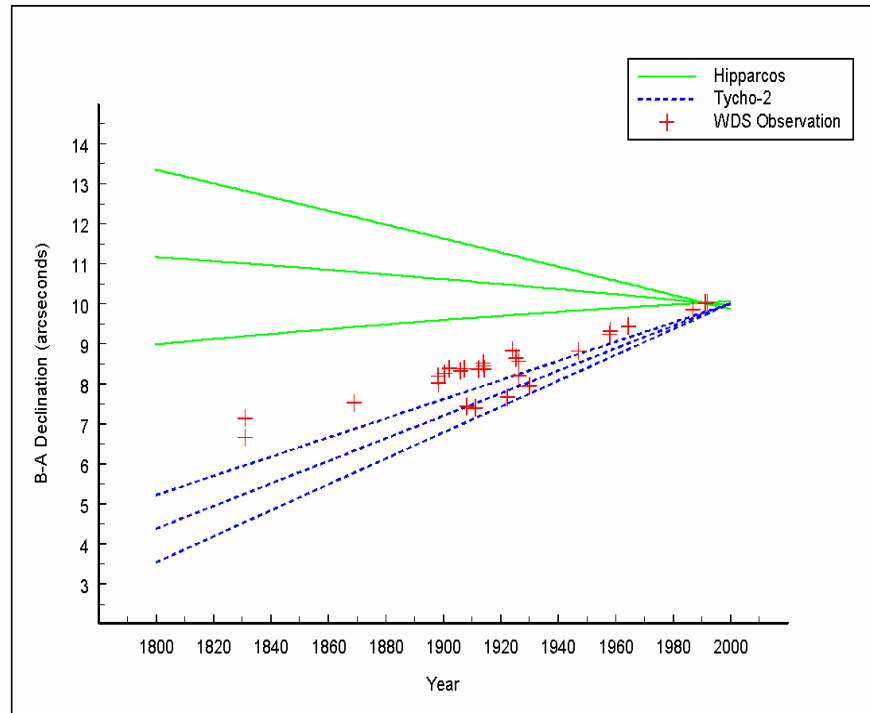
Observational measures recorded in the Washington Double Star (WDS) catalog (Mason et al. 2000) were used as an independent source of proper motion data for evaluating Hipparcos and Tycho-2 proper motions. The WDS is the largest repository available of double star observations. We identified WDS pairs in which both A and B components had separate proper motion determinations in both Hipparcos and Tycho-2 catalogs. We computed relative proper motions (B minus A) in RA and Dec from the individual WDS measures, then compared these relative proper motions to those derived from the Hipparcos and Tycho-2 catalog data for each component.

The WDS may seem to be a rather odd source of information on proper motions. Obviously such data are relevant only to stars that are members of double systems, and it provides data only on *relative* proper motions. Furthermore, one must be careful in selecting the WDS pairs for such analysis, since it is necessary to choose either optical doubles or wide binaries with very long periods so that nonlinear motion is negligible. For this pilot study, we selected 162 pairs (based on somewhat subjective criteria, listed below), although many more pairs could undoubtedly be used. All that having been said, the WDS data is of quite high quality and in many cases spans a century or more. In cases where the Hipparcos and Tycho-2 proper motions are significantly different for the stars in a pair, the WDS data can often be used to select the better values.

HIP 41953/41955 Right Ascension Difference



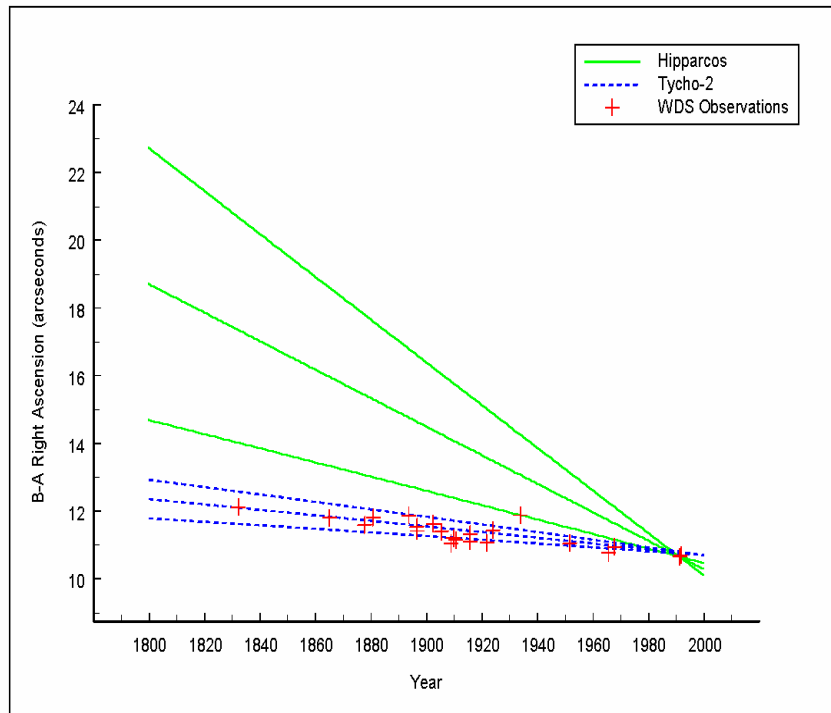
HIP 41953/41955 Declination Difference



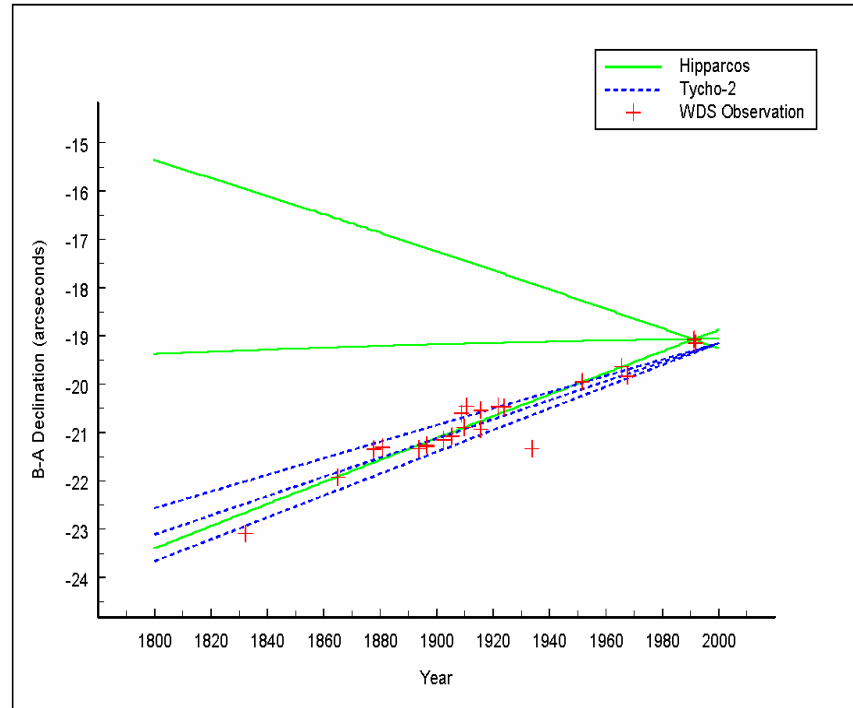
Example #1 of significant proper motion differences between Hipparcos and Tycho-2 resolved by means of WDS data.

Projection of relative motion of the components of the double star system HIP 41953 + HIP 41955 in right ascension (left) and declination (right). The projection derived from Hipparcos proper motions is shown as three green solid lines, with the nominal projection as the middle line, and plus and minus one-sigma lines on either side. The comparable Tycho-2 projection is shown as three dotted blue lines. The WDS observational measures, converted from separation and position angle to differences in RA and Dec, are shown as red crosses.

HIP 99569/99566 Right Ascension Difference



HIP 99569/99566 Declination Difference



Example #2 of significant proper motion differences between Hipparcos and Tycho-2 resolved by means of WDS data.

Similar to pair of plots on the left, but for double star system HIP 99569 + HIP 99566.

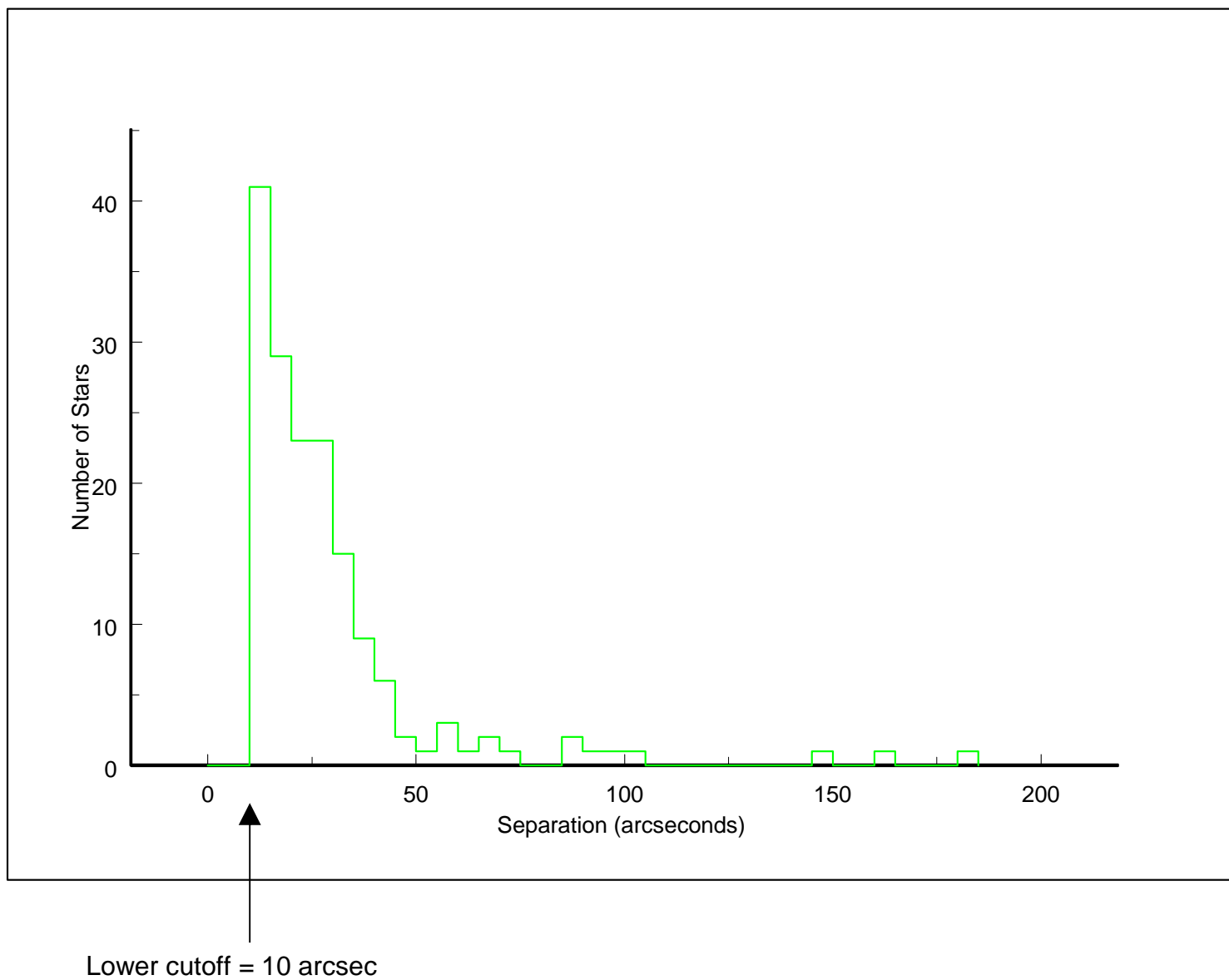
# The Sample

Since this was a pilot study to evaluate whether WDS data were appropriate for proper motion evaluations, we were conservative in the sample of stars selected for study. In particular, we wanted double star systems that were likely to have very long periods compared to the span of WDS observations, which in some cases was a century and a half. Furthermore, we wanted stars with good data in all three catalogs. Our selection criteria were:

- A component  $m_V < 8$ , B component  $m_V < 11$
- At least 15 observations in WDS
- Most recent measured separation  $> 10$  arcsec
- Difference between first and last measured separations  $< 5$  arcsec
- Independent proper motion determinations for A and B in Hipparcos (double entry systems)
- No systems known to have more than 2 components; no pathological stars

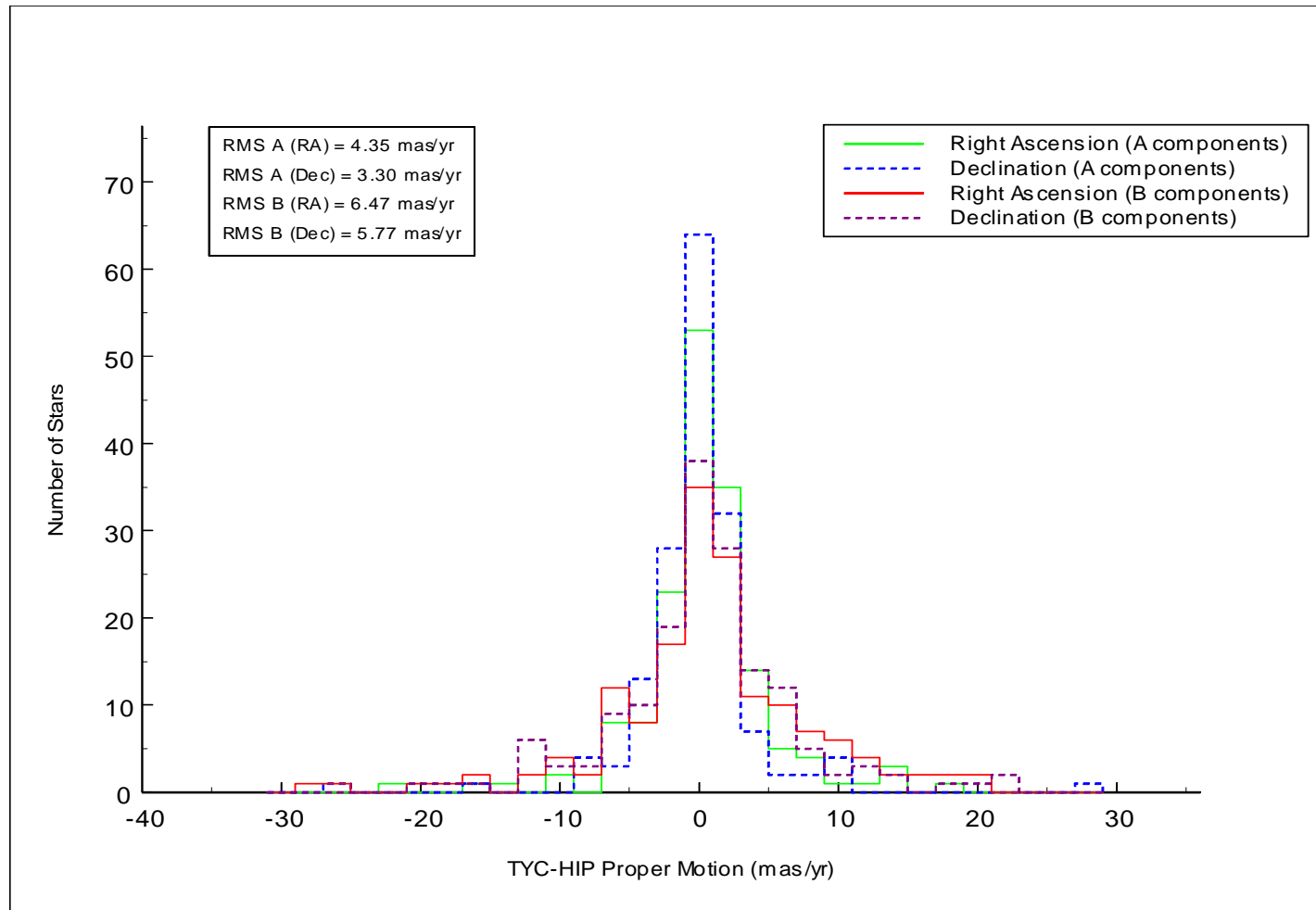
The result was 162 bright double systems, with an average visual magnitude of about 7 for the A components and 8 for the B components. Other statistics for this sample are shown in the plots to the right. Based on the parallaxes of components, over 4/5 of these double systems may be physical pairs, although crude estimates of the periods (actual orbits and periods are unknown) indicate that they are in fact so long that nonlinear orbital motion is negligible compared to the uncertainties in the data.

## Distribution of Double Star Separations



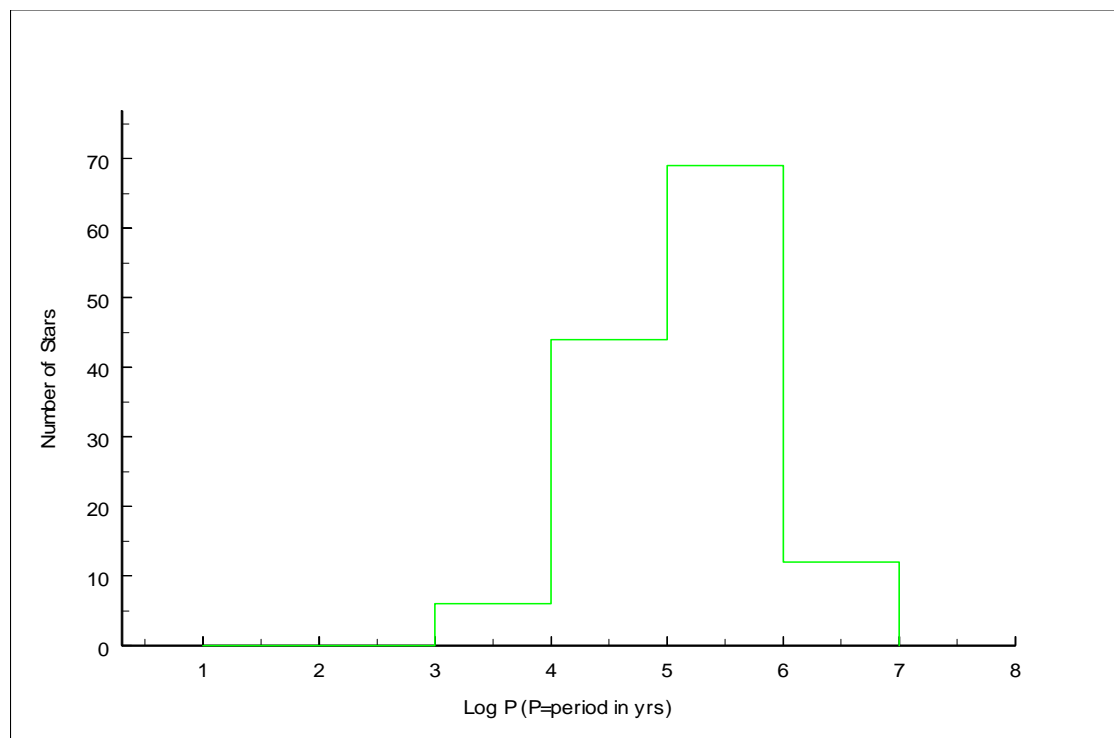


## TYC–HIP Proper Motion Differences (for Individual Stars)



Distribution of Tycho-2 minus Hipparcos differences in proper motion for the individual stars in the selected subset of 162 double systems. The distributions are wider for the B components than for A, probably because the B components are on average about one magnitude fainter. These distributions are significantly broader than those for the 98,909 stars in common in the two catalogs that are not known to be members of double systems. The evidently poorer quality of the data for the doubles may be related to Hipparcos satellite observational difficulties when more than one bright star was in the field of view.

## Distribution of Estimated Periods



Histogram of crude estimates of periods for the selected double stars, for the systems for which the parallaxes of the two components are the same within their errors (which is true for 82% of total sample). The periods were computed using the equation  $period = (separation/parallax)^{3/2}$ , which provides only an order-of-magnitude estimate for most pairs. The equation holds exactly only for pairs where the current physical separation is equal to the semimajor axis of the orbit and  $M \cos^3 i = 1$ , where  $M$  is the total mass of the system in solar masses and  $i$  is the inclination of the line joining the two components to the plane of the sky. Of course, none of these parameters are known. The relation between  $M$  and  $i$  holds at least approximately for many plausible configurations, e.g.,  $i=45^\circ$  and  $M=2.8$ . The current physical separation will always be equal to the semimajor axis for pairs in circular orbits, and the condition will also hold approximately for pairs in orbits of low eccentricity. However, for pairs in highly eccentric orbits, the most likely case is that the current physical separation is nearly twice the semimajor axis. For these cases the period is overestimated by a factor of up to 2.8, everything else being equal. Despite the many caveats, it is clear that almost all of the pairs that may be gravitationally bound have periods that are many orders of magnitude greater than the span of observations.

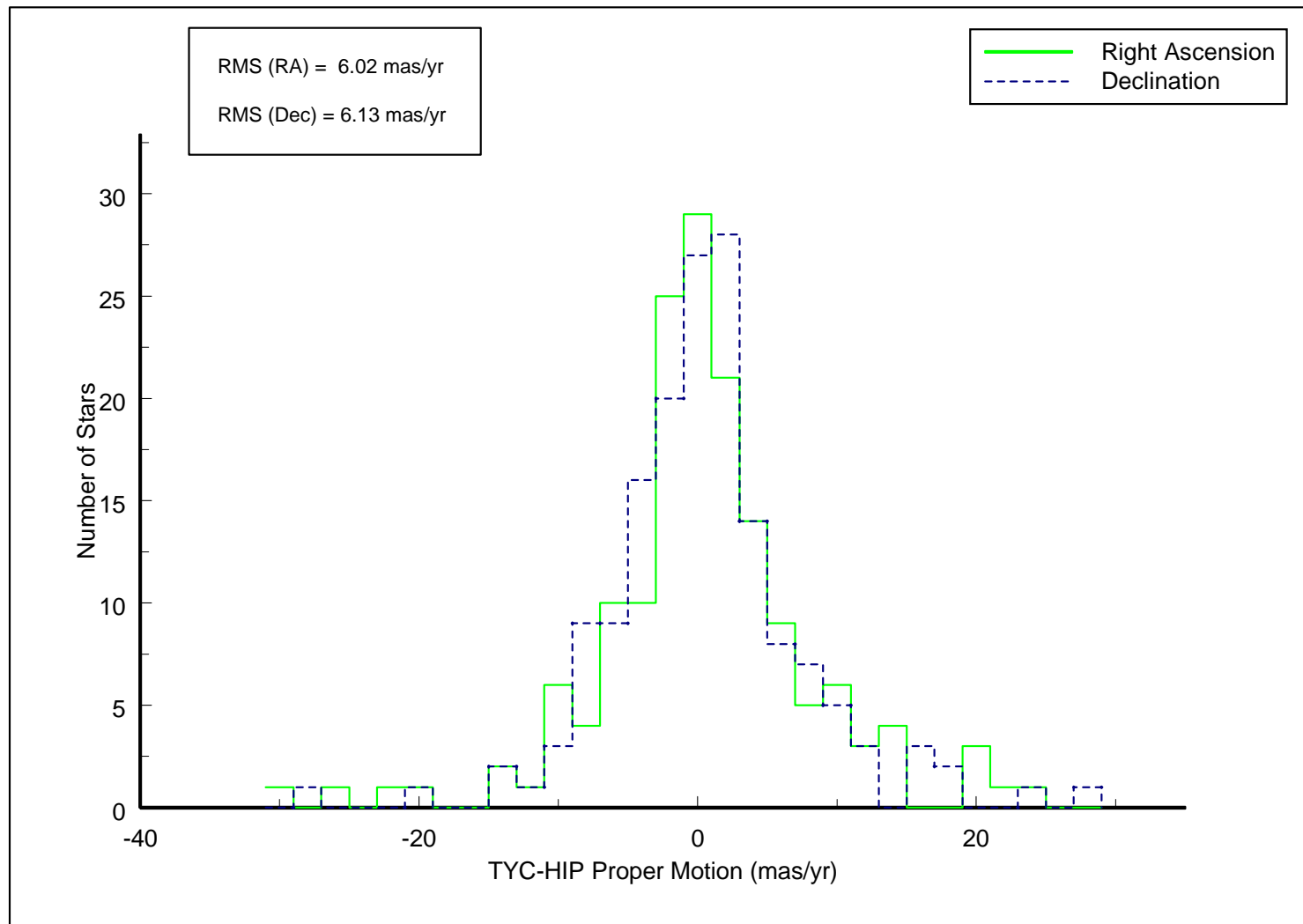
# Proper Motion Comparison: Three Data Sources

For the 162 selected double star systems, relative proper motions — that is, the motions of the B components relative to A — were computed from the observed data recorded in the WDS. For each system, WDS measurements of separation and position angle, which had been made at various epochs with respect to the equator of date, were transformed to  $\Delta RA$  and  $\Delta Dec$  values on the J2000 equator. Then, a least-squares solution for B–A proper motion (as well as relative position at epoch J2000) was computed. The computed relative proper motions were quite good for these solutions, with typical standard errors of 0.5–2 mas/yr.

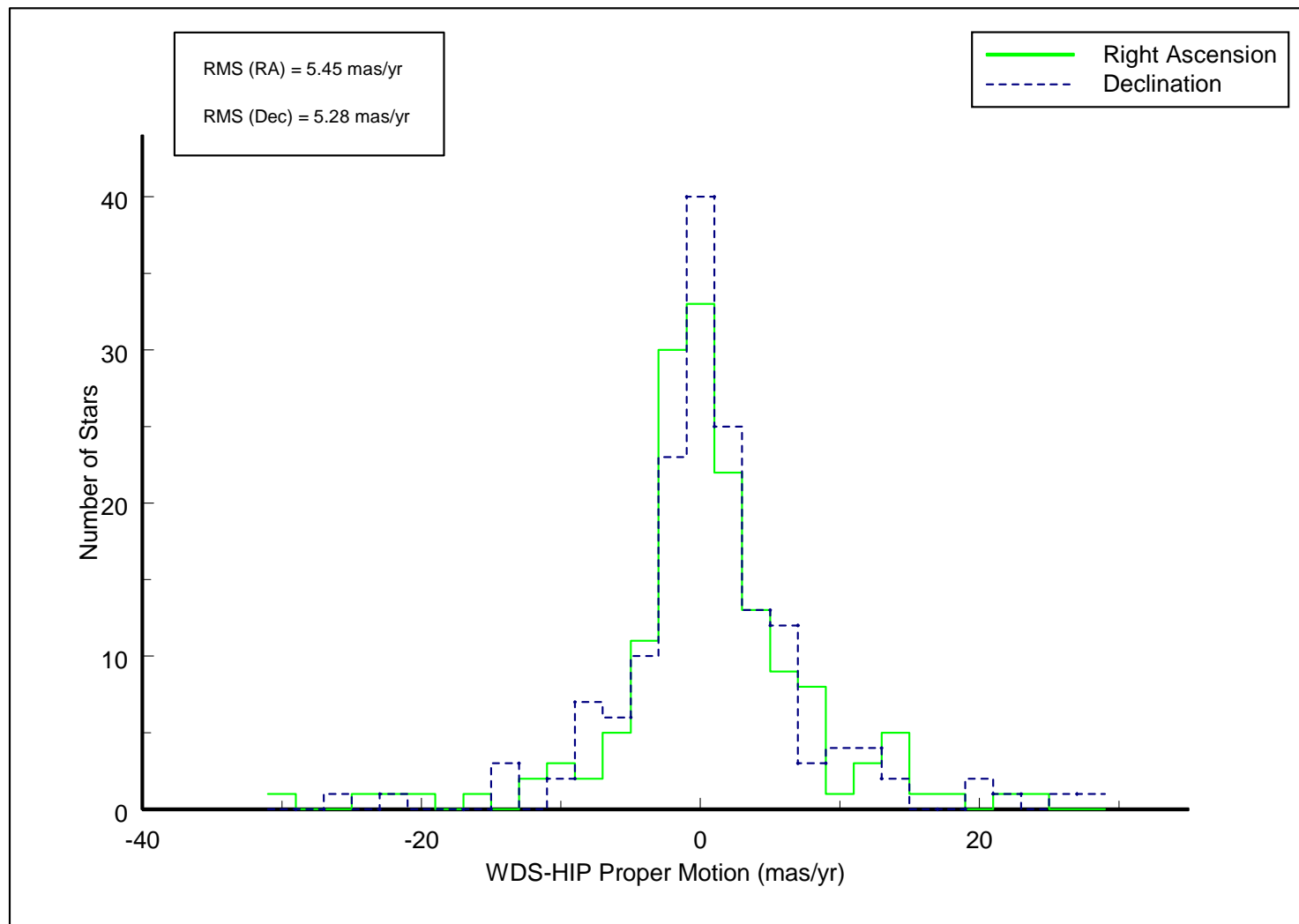
Relative proper motions were also computed for the same systems based on the proper motions for the individual components recorded in the Hipparcos and Tycho-2 catalogs.

The graphs on the right compare these three sets of data, as three two-way difference histograms. The  $1\sigma$  widths of each distribution of differences are indicated (not counting the few outliers with  $|\text{differences}| > 20$  mas/yr). The  $1\sigma$  width of the WDS–Tycho-2 distribution (3<sup>rd</sup> graph on right) is significantly less than that of the WDS–Hipparcos distribution (2<sup>nd</sup> graph on right). On the surface, this indicates that the WDS data is better matched to the relative proper motions derived from Tycho-2 — and, by implication, to the individual star proper motions from Tycho-2 — than to the corresponding Hipparcos data. It appears that the difference may be due mainly to fewer widely discrepant values in Tycho-2; that is, the WDS–Tycho-2 distribution has smaller “wings”. This needs to be verified.

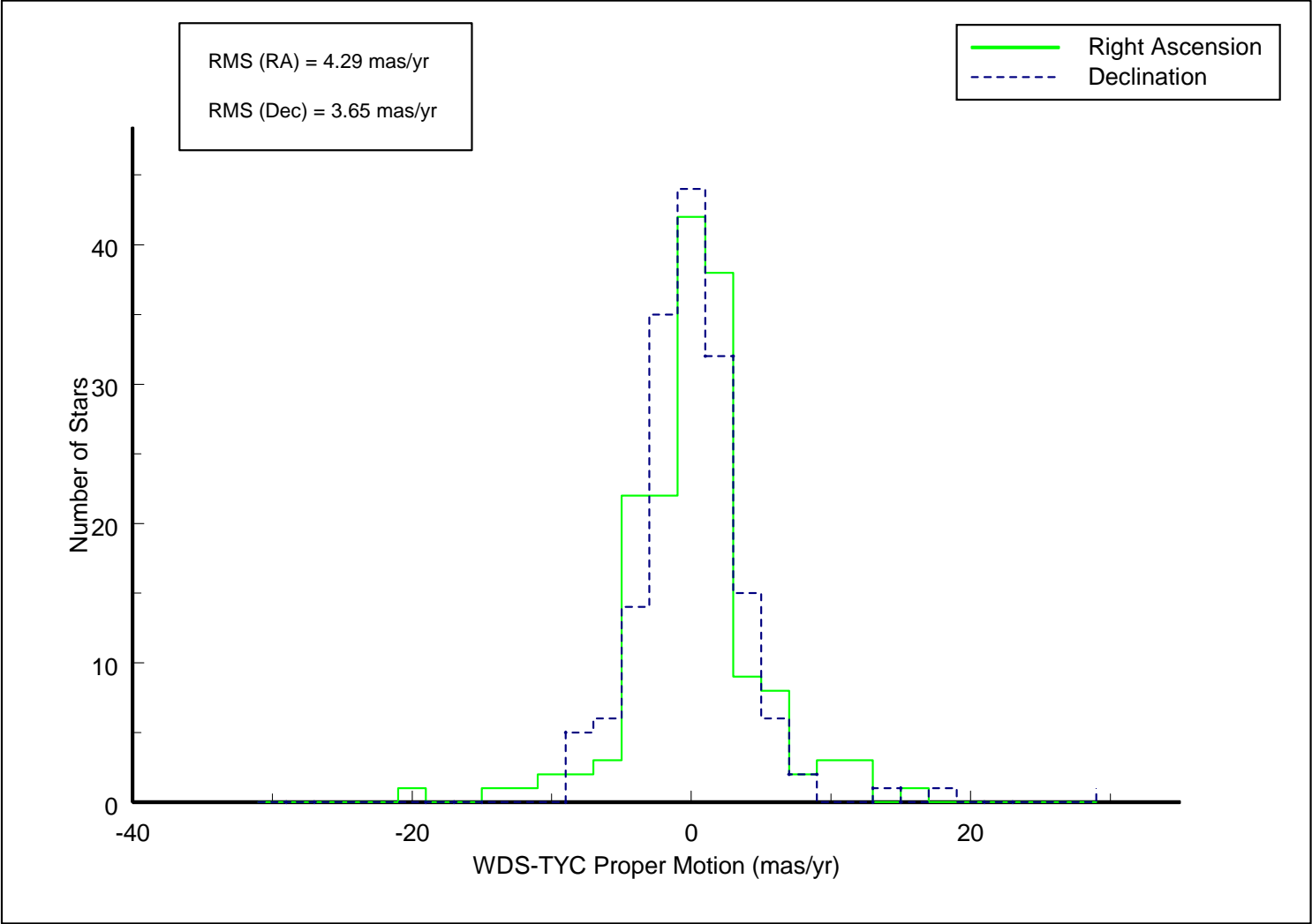
# TYC-HIP Relative Proper Motions (B-A)



# WDS-HIP Relative Proper Motions (B-A)



WDS-TYC Relative Proper Motions (B-A)



# Deriving External Errors for the Catalogs

Suppose  $\sigma_x$  and  $\sigma_y$  represent the mean external errors in the proper motions,  $\mu$ , in two independent star catalogs, x and y. Then a star-by-star comparison of the proper motions should yield a difference distribution with an RMS,  $\sigma_{y-x}$ , given by  $\sigma_{y-x}^2 = \sigma_x^2 + \sigma_y^2$ . The same relation holds if the relative proper motions,  $\Delta\mu$ , of stars in double systems are being compared, as is the case here. For the three difference distributions shown above, then, we should have:

$$\begin{aligned}(\text{measured RMS of } \Delta\mu_{\text{TYC}} - \Delta\mu_{\text{HIP}} \text{ distribution})^2 &= \sigma_{\text{TYC-HIP}}^2 = \sigma_{\text{TYC}}^2 + \sigma_{\text{HIP}}^2 \\(\text{measured RMS of } \Delta\mu_{\text{WDS}} - \Delta\mu_{\text{HIP}} \text{ distribution})^2 &= \sigma_{\text{WDS-HIP}}^2 = \sigma_{\text{WDS}}^2 + \sigma_{\text{HIP}}^2 \\(\text{measured RMS of } \Delta\mu_{\text{WDS}} - \Delta\mu_{\text{TYC}} \text{ distribution})^2 &= \sigma_{\text{WDS-TYC}}^2 = \sigma_{\text{WDS}}^2 + \sigma_{\text{TYC}}^2\end{aligned}$$

We have three equations in three unknowns, which can be solved for  $\sigma_{\text{HIP}}^2$ ,  $\sigma_{\text{TYC}}^2$ , and  $\sigma_{\text{WDS}}^2$ , the squares of the estimated *external* mean errors of the relative proper motions from our three data sources. It is only because of the three-way catalog comparison that such estimates of the mean errors in the individual catalogs can be obtained.

Solving, we obtain:

$\Delta\mu(\text{RA}):$	$\sigma_{\text{WDS}} = 2.44$	$\sigma_{\text{TYC}} = 3.53$	$\sigma_{\text{HIP}} = 4.88$	(units are mas/yr)
$\Delta\mu(\text{Dec}):$	$\sigma_{\text{WDS}} = 1.35$	$\sigma_{\text{TYC}} = 3.39$	$\sigma_{\text{HIP}} = 5.11$	

Furthermore, if we assume equipartition of the errors in the relative proper motions between the two components of each pair, then the mean error estimates computed above for the relative proper motions should simply be  $\sqrt{2}$  times the mean error of the individual star proper motions. The estimates of the external mean errors of the individual star proper motions in each catalog therefore are:

$\mu(\text{RA}):$	$\sigma_{\text{WDS}} = 1.73$	$\sigma_{\text{TYC}} = 2.50$	$\sigma_{\text{HIP}} = 3.45$	(units are mas/yr)
$\mu(\text{Dec}):$	$\sigma_{\text{WDS}} = 0.95$	$\sigma_{\text{TYC}} = 2.40$	$\sigma_{\text{HIP}} = 3.61$	

However, there are *many* caveats! The scheme depends critically upon the independence of the data in the three catalogs, and also requires that the differences all have near-Gaussian distributions. Neither of these conditions is strictly true for the catalogs analyzed here. For example, Hipparcos and Tycho-2 are not totally independent, since Hipparcos positions and proper motions were used to align the ground-based catalogs that were used in constructing Tycho-2. (Note also that the most recent update to the WDS, not used here, added data from Hipparcos and Tycho-2.) Two of the three distributions shown above appear to have broader wings than for a true Gaussian. The assumption of equipartition of errors between the two components does not quite hold for the Hipparcos–Tycho-2 comparison (see TYC–HIP graphs above for B–A and individual stars), probably because of small systematic errors in one or both catalogs that affect the proper motions of both stellar components but not their difference. Therefore, we must be very cautious before taking the above numbers too literally. However, they probably do indicate the *relative* ranking of the quality of the proper motions from the three data sources, at least for the sample of stars investigated here.



# Conclusions

- We have used observational data from the Washington Double Star (WDS) catalog to assess the proper motions listed in the Hipparcos and Tycho-2 catalogs for a small set of stars that are members of wide, bright double systems. The set of stars was selected to ensure that any nonlinear component of orbital motion was negligible for the time span of the observations.
- The data showed that, overall, the WDS data tended to favor the Tycho-2 proper motions over those from Hipparcos for this set of stars, although this trend might be mostly due to fewer “outliers” in Tycho-2 than Hipparcos. For many double systems, it may be possible to use the WDS data to improve the proper motions of the individual components, given some simple assumptions.
- By using three independent data sources, estimates of the *external* errors of the proper motions can be obtained. The errors derived in this way are  $\sim 3.5$  mas/yr for Hipparcos,  $\sim 2.5$  mas/yr for Tycho-2, and 1–2 mas/yr for WDS. These values are subject to many qualifications, but are not inconsistent with the respective formal errors for the subset of stars analyzed here. At the very least, they undoubtedly correctly rank the three catalogs for the reliability of their proper motion information for our subset.
- The Hipparcos data for our subset of stars, all members of wide double systems, are substantially poorer than that for the single stars in the catalog. This may be due to observational difficulties that occurred when more than one bright star was in the Hipparcos field of view.

# References

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Urban, S. E., Wycoff, G. L., & Makarov, V. V. 2000, AJ, 120, 501

Mason, B. D., Wycoff, G. L., Hartkopf, W. I., Douglass, G. G., & Worley, C. E. 2000, AJ, 122, 3466 (see also <http://ad.usno.navy.mil/ad/wds/wds.html>)

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